ABSTRACT

Large-scale digital fabrication of concrete, commonly referred to as 3D Concrete Printing (3DCP) is an emerging construction technology that uses digital 3D models to generate instructions for robotic printing systems. By reducing labor-intensive activities and increasing automation, 3DCP offers significant potential for improving construction productivity. However, current workflows remain fragmented, with digital information primarily communicated to printers while human workers perform contributory tasks such as placing printing supports and conducting visual inspections. These activities require close human–robot interaction and expose workers to safety risks. Furthermore, the absence of clear safety guidelines and the limited understanding of factors influencing industry adoption hinder the broader implementation of 3DCP. These challenges are associated with the underutilization of digital information and the lack of sensing and feedback mechanisms required to continuously update the process state and enable adaptive decision-making. To address these challenges, the overarching goal of this dissertation is to develop and validate an integrated digital twin ecosystem for large-scale 3DCP that enhances automation, coordination, quality assurance, safety, and technology adoption throughout the construction lifecycle.

To achieve this goal, the research investigates consecutive and interconnected stages of digital twin implementation, including (*i*) a *Digital Master* (DM) for planning and customization of printing strategies, (*ii*) a *Digital Shadow* (DS) to enable multi-robot collaboration for contributory manipulation tasks, and (*iii*) a *Digital Twin* (DT) for intelligent inline quality inspection. In addition, the research examines (*iv*) *safety considerations* associated with human–robot interaction in 3DCP and (*v*) the factors influencing the *adoption* of this emerging technology across different contexts and regions.

The results demonstrate that (*i*) a *DM* represented through a Building Information Model (BIM) can improve planning, coordination, and printing efficiency; (*ii*) a *DS* can coordinate multi-robot collaboration and reduce unsafe human involvement during operations; and a (*iii*) *DT* can provide proactive quality monitoring and intervention alert when printing deviations exceed acceptable tolerances. The findings also reveal that existing manufacturing and construction standards do not adequately address the unique safety requirements of 3DCP, and that contextual and regional factors can exert greater influence on technology adoption than technical considerations alone.

Based on these findings, this dissertation proposes a digital twin architecture composed of seven layers (i.e., digital, physical, sensing, perception, control, communication, and device) and a three-stage digital twin ecosystem (DM, DS, DT). Experimental validation using an industrial robotic arm and a mobile manipulator demonstrated the framework's ability to reduce unsafe human–robot interactions, automate quality inspection, and improve workflow coordination. The proposed architecture provides a replicable foundation for other digital fabrication and automated construction processes.

This dissertation contributes to the body of knowledge and practice by introducing a novel digital twin architecture for 3DCP, demonstrating the implementation of different digital twin stages for multi-robot applications, advancing the understanding of technology adoption in emerging construction technologies, and establishing a conceptual framework for safety considerations in 3DCP. Beyond this, this dissertation made broader impacts on safety by reducing human exposure to robotic operations and providing guidance for human–robot interaction, improving quality through automated inline inspection, increasing productivity by streamlining planning and automating contributory tasks, and extending technology adoption theory by highlighting the importance of contextual factors beyond technical considerations.